# Development of Advanced Surface Enhancement Technology for Decreasing Wear and Corrosion of Equipment Used for Mineral Processing

**ANNUAL TECHNICAL PROGRESS REPORT**

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Dr. Daniel Tao
Department of Mining Engineering, University of Kentucky
234E, MMRB, Lexington, KY 40506-0107

Dr. Craig A. Blue
Oak Ridge National Laboratory
P.O. Box 2008 MS6083
Oak Ridge, TN 37831-6083

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**University of Kentucky Research Foundation**
**201 Kinkead Hall, Lexington, KY 40506-0057**

**Oak Ridge National Laboratory**
**P.O. Box 2008 MS6083, Oak Ridge, TN 37831-6083**

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# ABSTRACT

Equipment wear is a major concern in the mineral processing industry, which dramatically increases the maintenance cost and adversely affects plant operation efficiency. In this research, novel surface treatment technologies, High Density Infrared (HDI) and Laser Surface Engineering (LSE) surface coating processes were developed for the surface enhancement of selected mineral processing equipment. Microstructural and mechanical properties of the coated specimens were characterized. Laboratory-simulated wear tests were conducted to evaluate the tribological performance of the coated components. Test results indicate that the wear resistance of ASTM A36 (raw coal screen section) and can be significantly increased by applying HDI and LSE coating processes. Field testing has been performed using a LSE-treated screen panel and it showed a 2 times improvement of the service life.

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# EXECUTIVE SUMMARY

This project is aimed at developing advanced surface enhancement technology for decreasing the wear and corrosion rate of mineral processing equipment by an order of magnitude. The proposed process is expected to be easily adaptable to automation and less expensive than currently used methods. Such performance improvement will result in energy savings of 2.45 x $10^{14}$ Btu/year. Significant efforts have been directed toward reducing wear of cyclones, pumps, heavy medium vessels, etc. used in mineral processing during the last two decades or so. Major progress has been achieved through the use of ceramic linings that have considerably increased the lifetime of hydrocyclones. However, little has been done to reduce the wear of screens, chains for conveyors, and piping where ceramic lining is impractical. The screen aperture increases as material wears, resulting in inconsistent aperture sizes and lower screening efficiency. This creates non-ideal feed to downstream operations, reducing their efficiencies. The wear of pipes, particularly the joint elbows, is another major concern of plant operators. The combination of corrosion and wear severely impacts the life span of chains, especially pin, bushings, and side plates. For horizontal conveyor systems, current materials used for chains include chrome-plated pins in an effort to minimize the combined wear/corrosion issues. However, stress-corrosion issues of chain components are continual problems. For inclined systems, corrosion issues are more limited; however, significant wear issues remain. Frequent replacements of screens, conveyors, and pipes increase equipment downtime and maintenance cost and reduce process efficiency. The development of advanced surface enhancement technology is of great interest for the mineral processing and coal preparation industry.

During the past year research efforts have been focused on the following aspects:

1. Thermite coating was successfully applied on ASTM A36 steel (raw coal screen) using HDI process.

2. The microstructural and tribological properties of the HDI-coated specimens were examined and the coated component showed increased microhardness as well as enhanced wear resistance compared to the untreated sample, which demonstrated a considerable potential of applying HDI coating process to extend mineral processing devices.

3. A new laboratory wear test instrument, dry sand abrasion wear tester, was built to better study the wear performance of the coated specimens.

4. Continued on-site testing has been performed.

# INTRODUCTION

## Wear In Mineral Processing

Mineral processing is the science of separating valuable minerals from the gangue minerals out of ores to produce basic materials such as coal, quartz, salt, copper and gold that are used in the industry and everyday life. Mineral processing usually includes several unit operations, including comminution, classification/screening, concentration/processing and post-treatment (e.g., product dewatering). The mineral processing industry deals with a very large tonnage of mineral ores and products. Equipment wear happens inevitably in every stage of the process, which increases the equipment maintenance costs and plant downtime and reduces the process efficiency of the plant. Wear is believed to be one of the most significant problems in the mineral processing industry. It is estimated that up to 40% operating costs of a mineral processing plant are caused by equipment maintenance (Laurila and Budge, 2000). The equipment wear problems that exist in each of the aforementioned processes are discussed as follows:

Comminution is referred to as the gradual reduction of a hard mineral to a fine powder by crushing or grinding for direct use or further processing. This includes liberation of a product, such as coal from non-coal material. It also includes primary crushing, where run-of-mine ore is reduced to a size small enough to feed a secondary crusher and rock is broken down to an adequate size for grinding. Mineral comminution, especially grinding, requires large energy costs and may account for more than half of hard rock processing energy costs (Wills, 1985). According to the mining annual review conducted by the Mining Journal (1999), approximately 29 billion kWh of electrical energy is consumed each year for size reduction. Therefore, wear issues associated with this energy intensive process of comminution have been extensively studied and many approaches, from optimizing the equipment design to the development of wear resistant materials, have been adopted during the past two decades (Durman, 1988; Norman, 1980). The wear issues regarding comminution equipment is beyond the scope of this research.

Screening is a critical unit process in mineral processing. Screen is the most commonly used device in the mineral processing industry to separate particles by size. Modern mineral processing would not be possible without efficient screening. In a coal processing plant, screening accomplishes sizing by passing coal of different sizes through a series of screens, each of a decreasing size. The individual screen discharges are then directed into different screen products for subsequent processing or sale. In processing industry, screens are also used for product dewatering, heavy media recovering, etc. (Leonard and Hardinge, 1991). During screening process, the aperture size increases as material wears, e.g. Figure 1, resulting in inconsistent aperture sizes and lower screening efficiency because more oversize particles may report to the underflow, which as a result creates non-ideal feed to the downstream processes.

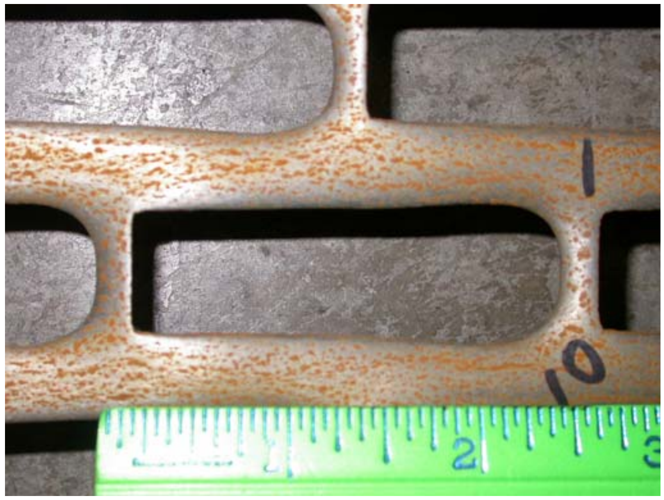

Figure 1. A failed screen panel due to wear

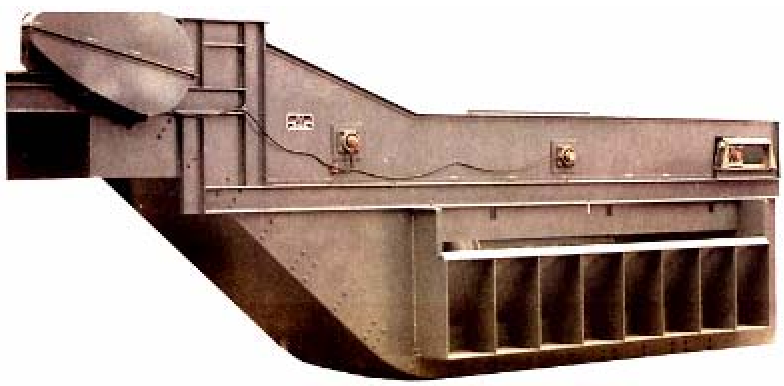

Figure 2. A typical dense medium vessel

Concentrating is the process of separating valuable minerals from their ores using the physical or physico-chemical property differences of different components. There are many mineral concentrating processes used in the coal and mineral processing industry. Dense medium separation process is the most widely used coal processing method, which accounts for 49% of the processing units used worldwide (Laurila, 1998). There are two types of dense medium separators in mineral processing, which are dense medium cyclone and dense medium vessel, as shown in Figure 2. Since ceramic linings have been developed and commercially used in dense medium cyclones to protect their inner walls (Foster, 1996), the wear enhancement of dense medium cyclones will not be covered in this research. It should be noted that the wear issues concerning heavy medium vessels which accounts for 26.3% of the coal preparation units in the United States (Laurila, 1998) have not been well addressed. In a heavy medium vessel, a feed sink plate is usually used to direct the feed (raw coal and dense medium suspension) downward into the vessel so that particles do not raft across the width of the bath. Thus, the plate is subject to high wear as the feed slides down along the plate into the vessel.

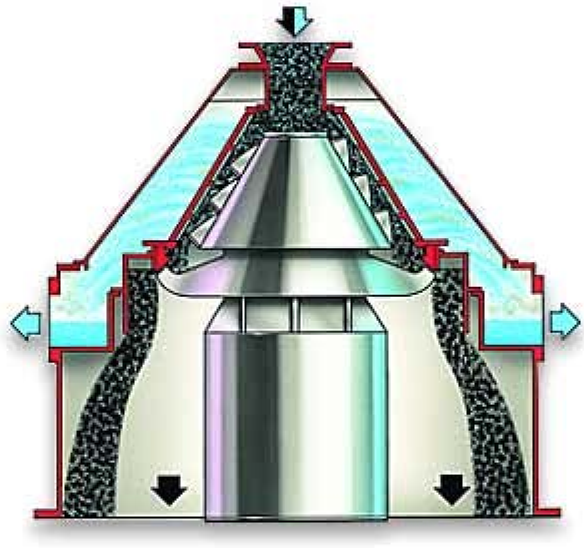

Figure 3. Schematic of a dewatering centrifuge

The purpose of product dewatering is to control the post-processed product, e.g., clean coal, to an acceptable moisture level. Centrifuge is commonly used in the coal preparation and mineral processing industry for product dewatering. A typical perforate-basket centrifuge is schematically shown in Figure 3. Centrifuges achieve separation by means of the accelerated gravitational force achieved by a rapid rotation. The separation is similar in principle to that achieved in a gravity separation process. The driving force is higher because it is resulting from the rotation of the liquid, unlike gravity sedimentation, where the driving force is from the difference in density between the solid particles and the liquid. The centrifuge separation is achieved with a force 1000 to 20000 times of the gravity. The centrifuge screen is subjected to wear when particles are pressed against the screen surface due to the high centrifugal force generated by the fast rotation.

It should be mentioned that the literature survey conducted by the author indicated that the equipment wear issue in mineral processing has not been well addressed. In the past, research efforts have been mostly focused on the wear problems of the energy-intensive comminution equipment. Little work has been done on the study of wear enhancement of screening, heavy medium vessel and dewatering equipment. Although the energy consumption of these devices is much lower than that of the comminution equipment, wear deteriorates the separation performances of these devices and, as a result, affects the overall plant process efficiency is affected.

During the last two decades, significant efforts have been made to reduce wear of cyclones, heavy medium vessel, pipe lines and pumps which are widely used in mineral processing. The goal has been realized by using the ceramic linings to coat the inner surface of the high wear equipment (Foster, 1996). The different shapes of ceramic linings are installed inside the vessels and cyclones, which are much harder and have stronger wear resistance. They can greatly increase the lifetime of mineral processing equipment (Nonnen et al., 1985).

However, research has not been effectively performed to reduce the wear of screens, chains for conveyors and pug mill paddles for coal mixing, which have to be replaced very often as a result of wear. Due to size and complex geometry of screen, it is not feasible to apply ceramic lining to the screen. As the screen wears, the screen openings will become wider and wider. During this process, the screen loses the consistency of aperture and reduces the screening efficiency. The increased screen openings also reduce the efficiency of downstream operations due to non-ideal feed to them. Furthermore, the replacement of screens will increase the plant shutdown time and reduce the overall plant efficiency. The development of advanced surface enhancement technology and its application to screens and other equipment to enhance their wear lives are strongly desired by the mining and mineral processing industry.

**High-Density Infrared (HDI) Surface Coating**

High-Density Infrared (HDI) process is a novel technology developed by the Oak Ridge National Laboratory (ORNL). This process involves producing infrared heating with extremely high power densities of up to 3.5 $kW/cm^2$ using a unique plasma arc lamp (PAL) system.

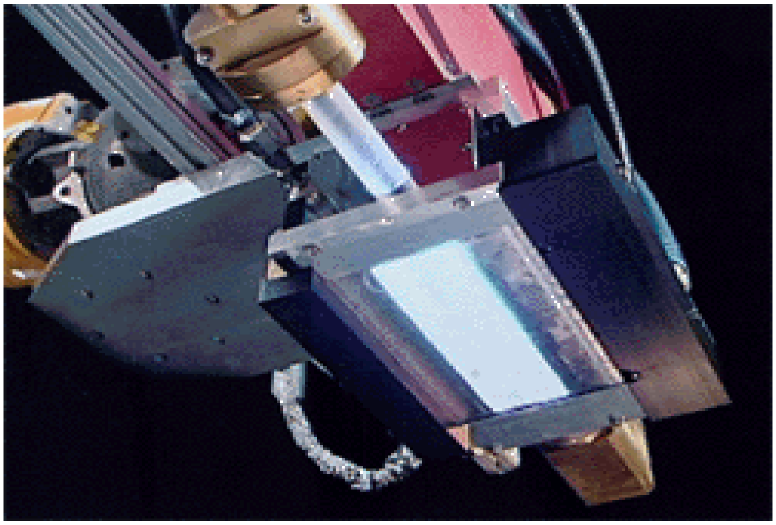

Figure 4. Plasma arc lamp

The lamp, as shown in Figure 4, consists of a quartz tube of 3.175 cm in diameter and 10.16 cm, 20.32 cm or 38.1 cm in length. The lamp is sealed at the ends where the cathode and anode are located. Deionised water mixed with argon or nitrogen gas enters at the cathode side through high velocity jets impinging at a given angle. Due to the high velocity and pressure, the water is then impelled to the wall of the quartz tube and spirals down the length of the tube in a uniform film of 2-3 mm thick. This water film serves two purposes: to cool the quartz wall and to remove any tungsten particulates that may be expelled from the electrodes. The gas moves in a spiral fashion through the center of the tube, and a capacitative circuit initiates the plasma which has a temperature in excess of 10,000 K, is stable and produces a radiant spectrum of 0.2-0.4 μm. The plasma is absorbed by metal surfaces with high efficiency. The powder coatings of wear resistant materials are also highly absorbing, because the open areas act like black bodies. Figure 9 shows an actual plasma-infrared lamp used at ORNL.

Infrared heating is an inherently clean, noncontact heating method that provides rapid-response energy fluxes capable of heating rates in excess of $3000^{o}$ C/s, rapid power-level changes, high cooling rates and a controllable temperature-gradient. Coating materials are fused by the PAL, yielding metallurgical bonding between coating and substrate. It was demonstrated that the method could fuse and metallurgically bond coatings and steel substrates without convective mixing, providing a new means for the rapid thermal processing of surface coatings (Engleman et al., 2002). It has been applied to the treatment of metals (Blue et al., 2000; Muralidharan et al., 2004). HDI surface treatment process has been successfully applied in the wear parts used for bulldozers manufactured by the Caterpillar Inc. More than 5-fold of wear enhancement has been achieved (Blue, 2002). Advantages of using a plasma radiant source to fuse coatings include:

- Large area coverage (3.175 × 35 cm in a line focus and up to 10 × 20 cm in a uniform irradiance)
- No convective mixing of coating material with the base material
- Rapid cooling of coating material
- Minimal effects on base material
- No degradation of carbide reinforcements in coating
- No temperature limitation (can readily melt tungsten - melting point = $3410^{o}$ C)

## Laser Surface Engineering (LSE)

Steels are the most common materials of construction for the equipment used in coal/minerals mining and processing industry. Several reasons for using steels include: being the lowest cost material, readily manufacturable into complex shapes, and heat-treatable by several techniques to obtain a range of surface and bulk properties. Surface coating as a manner of equipment wear life enhancement has been well established in engineering applications and many coating techniques have been extensively studied (Dowson and Taylor, 1985). Today, coatings are widely used for many purposes including the surface enhancement of different steels. Among the many surface treatment processes that are available today, lasers provide a unique tool for high quality surface modification. Many surface-related failures by mechanism involving wear, corrosion, erosion or high temperature oxidation can be minimized by laser surface modification (Mazumder, 1996; Steen, 1995). Surface modification using laser can take place in a variety of forms, depending on laser type and the materials to be treated.

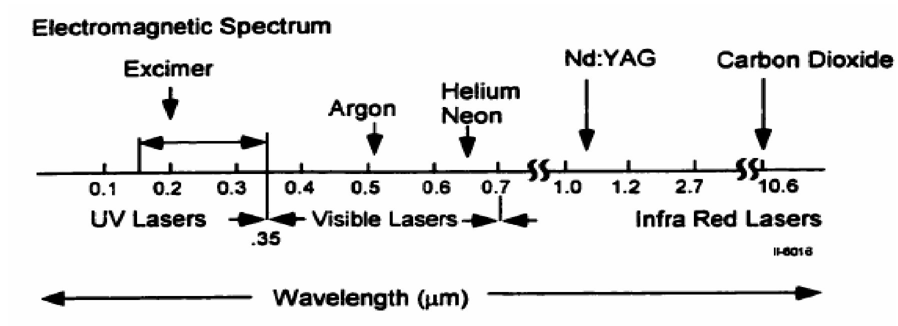


Figure 5. The wavelengths of different lasers in the electromagnetic spectrum

There are three types of lasers that are of sufficient energy and robustness that are used for surface treatment (Folkes, J., 1997) which are Carbon Dioxide (CO2) Laser, Neodymium-doped Yttrium Aluminum Garnet, (Nd:YAG) Laser and Excimer Laser. Figure 5 shows the location of some of the lasers in the electromagnetic spectrum (Folkes, 1994).

The carbon dioxide laser can be pulsed or continuous wave and ranges in power from typically 0 to 10 kW. It has an output wavelength in the far infrared, in the region of 10.6 μm. This wavelength is relatively long so generally the surface modification occurs by heating effects. The energy density and interaction time between the laser and the substrate, as well as the ability of the surface to absorb this wavelength are the main factors that determine the resulting surface modification.

The Nd:YAG laser can be pulsed or continuous wave and ranges in power from 0 to 3 kW. This output wavelength is 1.06 μm which is shorter than the carbon dioxide laser but still in the infrared region. Thus, the surface modification occurs by heating effects, however coupling the laser radiation into the surface tends to be easier due to the shorter wavelength.

The Excimer laser is pulsed and ranges in energy from 0 to 600 J. There are several different excimer lasers depending on which gas is used inside the system to achieve the laser action. The output wavelength is in the ultra violet region (200 ~ 400 nm). These wavelengths are relatively short and generally the surface modification occurs by a combination of photon interaction and heating effects. Since the wavelength is short the surface interaction/coupling of the laser into the surface is paramount in understanding the process.

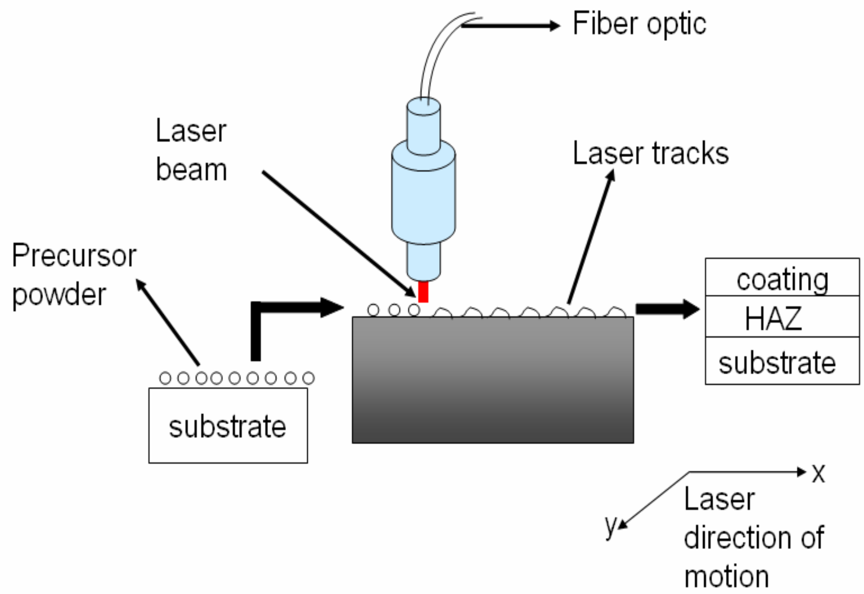


Figure 6. Schematic of the LSE process

Typical laser surface modification processes include (1) transformation hardening, (2) surface melting, (3) surface cladding, (4) surface alloying and (5) other techniques (surface smoothing, texturing, coating removal and micromachining, etc.). Due to the overlapping of the various laser surface modification processes, a new term "Laser Surface Engineering (LSE)" was proposed by Agarwal (1999) and therefore LSE was used in this proposal. A typical LSE process is schematically shown in Figure 6.

Laser surface engineering is known as a non-equilibrium synthesis involving high heating and cooling rates ($10^3$-$10^8$ K/s), which leads to the development of a wide variety of microstructures with novel properties that can not be achieved by any conventional processing technique (Mazumder, 1996). Other features of laser surface engineering include (Dahotre, 1998):

- High coating thickness (up to 0.8 mm)
- Metallurgically bonded coating
- Non-equilibrium synthesis process leading to the development of novel phases
- Precise control of processing parameters
- Beam can be shaped for a variety of energy distributions
- High flux densities (>$10^4$ w/cm$^2$)
- Laser beam transport to remote locations via fiber optics
- Allows for the processing of a wide variety of part configurations
- Amenable to automation

# EXPERIMENTAL

## Materials

The mineral processing industry requires materials having strength, toughness, wear and corrosion resistance. It should be noted that coating steels using high energy process such as laser with ultrahard ceramic particles has been developed to meet the extreme requirements of wear, oxidation and corrosion resistance (Agarwal, 2000; Khedkar et al., 1997). As a result, metallurgically sound interface between the coating and the substrate can be formed. However, as the physical properties such as thermal expansion coefficient (CTE) between the ceramic and the steels usually are different, cracks usually develop at the ceramic/steel interface as well as within the coating during the rapid solidification and cooling progress (Agarwal et al., 2000). The use of binders in coating materials can promote the good adhesion between the coatings and the steel substrates. For example, iron has been revealed as an excellent binder for Ti-based coatings on steels (Raghunath et al., 1995).

The word "thermite" is usually used to describe exothermic reactions which involve reduction of metallic oxides with aluminum to form aluminum oxide and metals or alloys (Wang et al., 1993). WC has high hardness, good strength and is stable at high temperatures (Chong et al., 2001). Thermite+WC coating powders [($Fe_3O_4$-34.4Al)-60WC, wt%) were used as coating precursor in the present investigation.

The substrate used in this investigation was a raw coal screen panel (1.22 m × 0.30 m × 8 mm, ASTM A36 steel) obtained from a coal preparation plant in Eastern Kentucky. The aperture size of the screen is 50.8 mm × 15.9 mm. Chemical compositions of ASTM A36 steel are listed in Table 1 (ASTM, 2003a).

Table 1. Chemical composition (in wt. %) of ASTM A36 steel

| Element | C | P | S | Si | Cu | Fe |
|---|---|---|---|---|---|---|
| Weight, % | 0.25 | 0.04 | 0.05 | 0.4 | 0.2 | Balance |

## Coating Preparation Using HDI

Screen sections (76.2 mm × 76.2 mm ×8 mm) cut from the raw coal screen panel was sand blasted to remove residual oxide scale and silica from the surface. The sections were further cleaned by using acetone and methanol in an ultrasonic cleaner for 5 minutes prior to spraying the coating precursor on the surface. The screen section was then placed under the PAL lamp with a preset energy level of 800 A. The selection of 800 A is based on trail-and-error method. One lamp pass was made at a traverse speed of 10 mm/s with a stand-off distance of 1 cm from the lamp to the sample surface.

**Sample Characterization**

Figure 7. Allied TechCut10™ Abrasive Cut-Off Saw

The characterization work is to investigate the mechanical, microstructural as well as tribologcial properties of processed specimens. The scope of microstrural characterization includes observation the bonding of the coating/substrate interface, phase distribution in the coating system. The specimens were cut from each sample with Allied TechCut10™ Abrasive Cut-Off Saw (Figure 7). The specimens were then mounted using epoxy resin with cross-section of coating-substrate interface exposed outside. The resin mounted specimen was easy to handle and ensured that the exact cross-section surface was polished. The mounted specimens were polished by mechanical grinding with a series of sand papers from coarse to fine (labeled with the following numbers: 200, 400, 600, 800, 1000 and 1200 grits). The purpose of this procedure was to remove the damages produced during cutting process. After the specimens were ground over the finest sand paper, the final step was to finish up on a polishing cloth with 0.3 µm alumina paste to obtain scratch free surfaces. This step was to remove any scratches or damage generated by the grinding.


Figure 8. Hitachi S-3200 SEM

The scratch free specimen surfaces were then etched to reveal the grain structure of the metallic phases. 2% Nital (98 ml ethanol + 2 ml nitric acid) was used as the etchant. The etchant did two things to the specimen surface. First, it chemically removed the deformed thin layer on the surface which was produced during the polishing process. Second, the etchant selectively attacked the highest energy sites on the surface without affecting the others. As a result, different crystal orientations, grain boundaries, precipitates, phases and defects were showed distinctly under the microscopy for the microstructure investigation. A Hitachi S-3200 scanning electron microscope (SEM, Figure 8) was employed to perform the microstructural characterization.

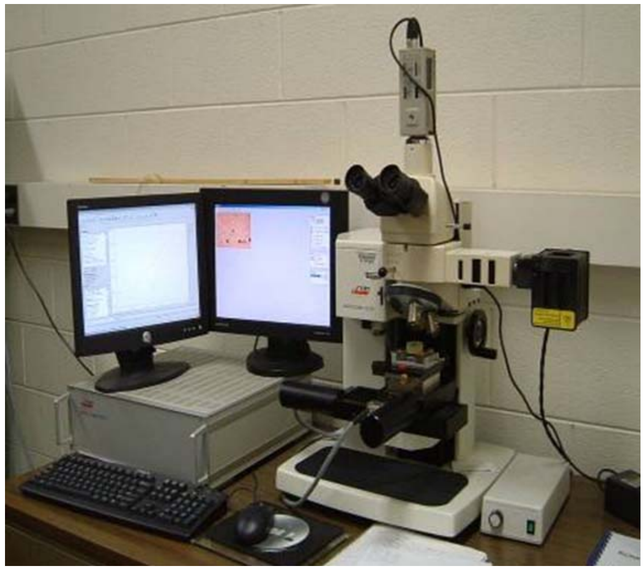

Figure 9. Microindentation tester

The mechanical properties was be examined by microindentation from which coating hardness profile can be achieved. Microindentation behavior of the coating and substrate will be studied at different loads. Figure 9 shows the indentation instrument (Micro Photonics, Irvine, CA) used in this research.

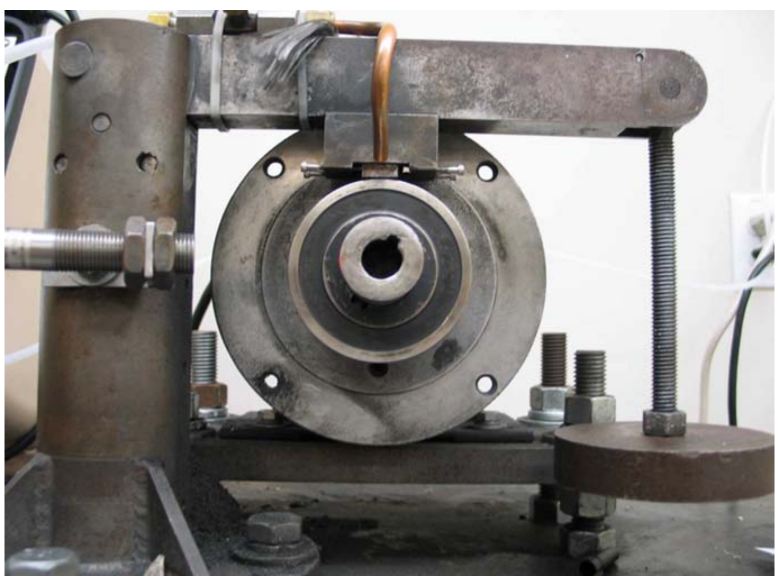

Figure 10. Block-on-ring tribometer

The wear resistance of coated specimen was tested in lab using an in-house constructed block-on-ring wear test machine (Figure 10). Each coated specimen will be slid against a hardened tool steel ring (HRC≈60, D = 82 mm). The ring's rotating speed is controlled at 1000±20 rpm. Specimen weight loss was measured after each successive

2 minutes for a total test duration of 20 minutes. A normal load of 10 lbs (4.54 kg) was applied on the specimen during the test.

**New Wear Test Equipment**

According to ASTM standard (ASTM, 2003b) abrasive wear is defined as "the wear due to hard particles or hard protuberances forced against and moving along a solid surface." Extending the wear lifespan of coal screens is a major goal for this project. Extensive investigation on screen wear indicates that abrasive wear plays an important role to cause the failure of a coal screen panel. Therefore, it is necessary to evaluate the abrasive wear performance of the coatings developed in this research.

A new lab wear test machine was designed and constructed in the Laboratory of Department of Mining Engineering at the University of Kentucky for further study the wear behavior of the coatings developed in this project. The purpose of this device is to evaluate the coating wear performance under abrasive conditions. The machine was designed to accommodate ASTM G65 standard. A schematic diagram of the test apparatus is shown in Figure 11.

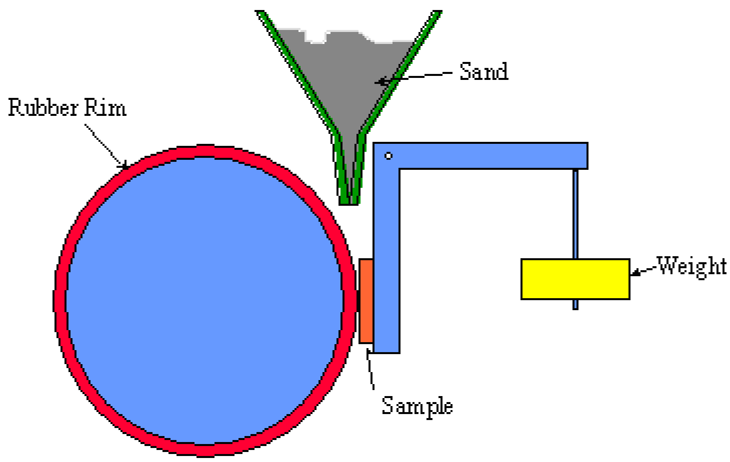


Figure 11. Schematic diagram of abrasive wear tester

**On-site Testing**

The coatings that exhibited excellent wear performance in laboratory were selected for preliminary industrial trials. It should be noticed that laboratory testing is no substitute for in-service experience due to the increased complexity of the operating environment. In this research, field testing of coated raw coal screen panels was performed at the Big Creek Processing Plant (Sidney, KY) of Sidney Coal Company Inc. Big Creek Processing Plant is a coal preparation operation with a processing capacity of 12 Mt of raw coal annually. The plant uses two screens for raw coal sizing process, each consisting of 40 panels (Figure 12). The raw coal screen panels provided by Sidney Coal were made of ASTM A36 steel with a dimension of 1.21 m × 0.3 m × 6 mm. The opening size of the panel is 50 mm × 13 mm.

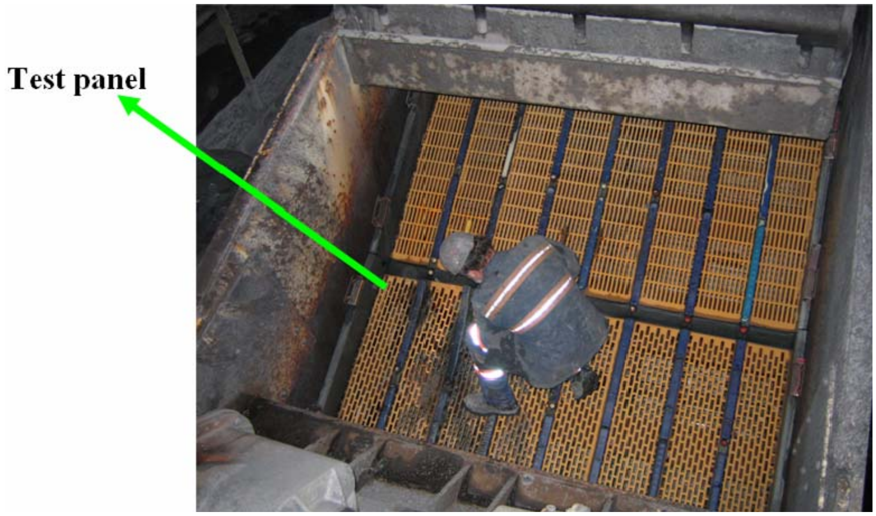


Figure 12. On-site test of coated screen panel

Three LSE-treated screen panels, named as No.7, No. 8 and No.9, respectively, have been tested at the Big Creek Processing Plant during the past year. The coating process information for the three panels is listed in Table 2.

Table 2. Test screen panels

| Test Panel | Coating | Laser power W | Laser speed mm/min |
|---|---|---|---|
| No.7 | Metco 12C | 2000 | 1500 |
| No.8 | Metco 12C | 2400 | 4500 |
| No.9 | (Ni-10P)-50$TiB_2$ | 1250 | 1500 |

The test panel was installed on the high-wear position of one of the two raw coal screens in the plant. One screen handles around 800 ton/hr raw coal. The screen operates 24 hours/day, and the plant is shut down 12 hour for maintenance every week. Weight loss of the test panel and size variations of specified openings on the test panel, as schematically shown in Figure 13, were measured every other week.

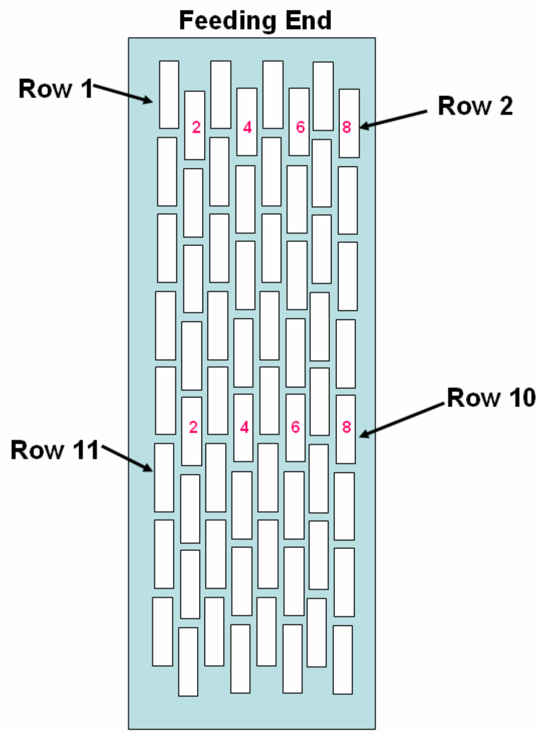


Figure 13.  Schematic of a test panel

## RESULTS AND DISCUSSION

### Microstructure

Figure 14 presents a cross sectional micrograph of the coated specimen. Three regions which are coating, HAZ (heat affected zone) and substrate can be easily identified. The presence of a transitional HAZ zone can be attributed to the high temperature attained during HDI treatment which austenitized the steel in the interfacial region, transforming it to martensite.

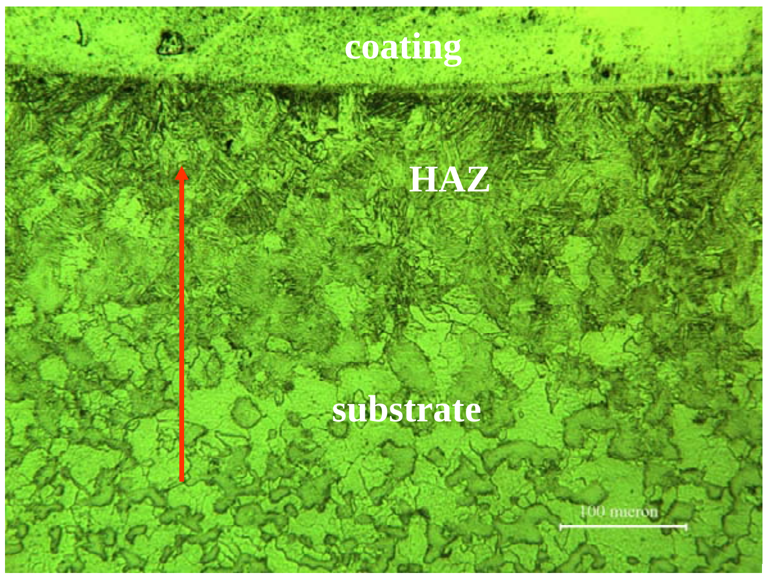


Figure 14. Micrograph of the coated sample

Figure 15 presents an SEM image of the coated specimen. It can be found that WC particles distribute uniformly along the coating depth. WC is a notable wear resistant material in coating application (Przybylowicz and Kusinski, 2001), and therefore the uniform distribution of WC is expected to improve the hardness of the whole coating layer. Dentrites formed uniformly in the coating zone, which is another feature that indicates refined microstructure can be obtained through the HDI coating process. Figure 15 also shows that the coating is metallurgically bonded to the substrate, significantly reducing the chance of coating delamination and improving wear performance.

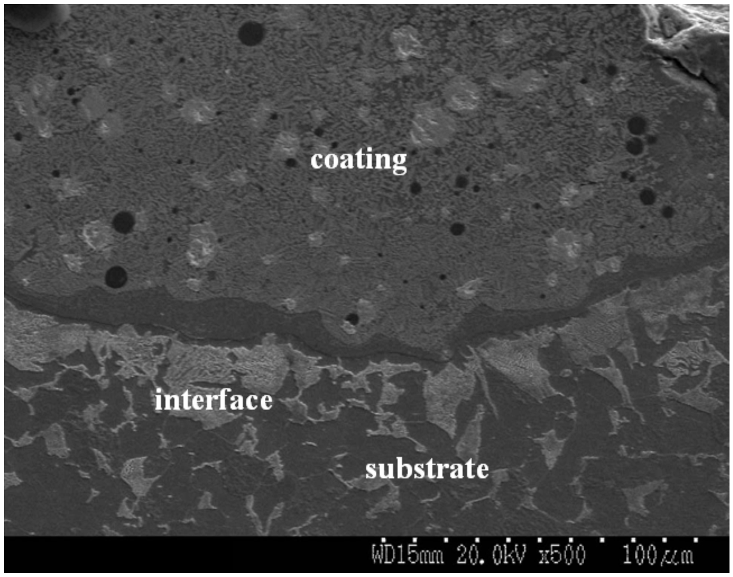


Figure 15. SEM image of the coated sample

**Microhardness**

The Vickers hardness profiles of the two specimens are depicted in Figure 16. One can see that the microhardness of the coating is much higher than that of the untreated screen substrate. In the meantime, it is noticed that there is a gradual decrease of hardness values from the coating to the substrate. The average hardness of the coating is around 830 HV and it deceases to 185 HV in the substrate. The average microhardness at the interfacial and the heat-affected-zone (HAZ) is 300 HV and 235 HV, respectively. The gradual decrease of microhardness is in agreement with the microstructure evolution observed in Figures 14 and 15.

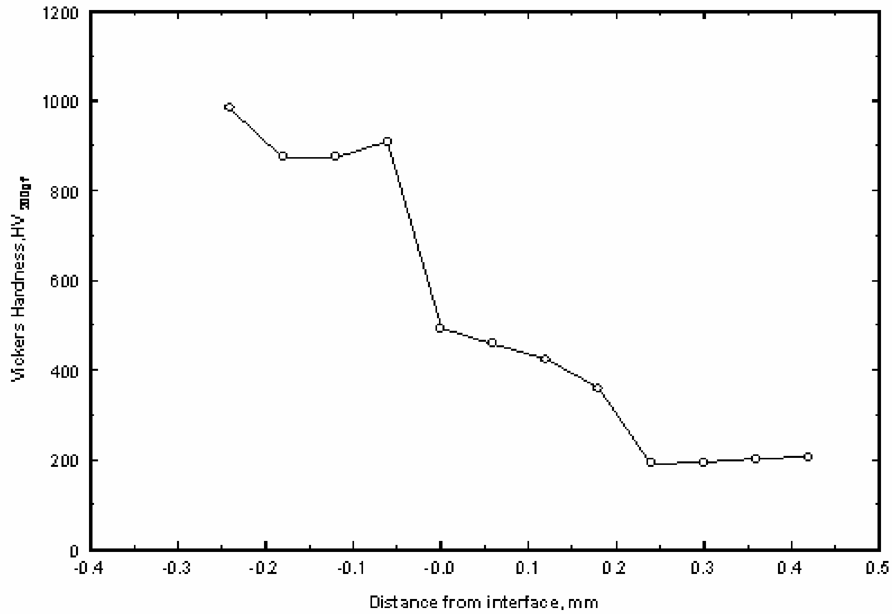


Figure 16. Microhardness profile of the sample

The high coating hardness of the specimens obtained by the two different approaches can be attributed to the addition of large amount of WC which is a typical material of high hardness. However, the microhardness of pure WC is about 3000 HV (Cutler, 1995); the coating micronhardness values obtained in the present study were significantly lower than that. This is mainly because the coatings are composite in nature. Other possibilities include the formation of additional phases. Microhardness obtained in this study basically represents the average hardness of the different phases. Further investigation using nanoindentation and TEM techniques can provide a more precise measurement of the hardness of individual phases.

**Wear Testing**

The block-on-ring dry sliding wear test results are presented in Figure 17 which compares the cumulative weight loss vs. test time for the coated and uncoated specimens for a screen section over a 20 minute test period. It can be easily seen that the wear resistance of the coated specimen in terms of total weight loss is significantly higher than that of the untreated screen section. Under the present test conditions, the wear rate of the thermite-coated coupon is about 6 times lower than the uncoated screen.

During a sliding wear process, the asperities of the weaker material may shear off and transfer to the opposite surface (Kelly et al.,1998). A wear rate increase of a coated component after a given period of time often indicates the smoothing and /or breaking off of hard asperities from the coating (Agarwal and Dahotre, 2000). Figure 17 shows that the wear rate (the slope the curve) of the HDI-processed coupon was rather stable during the entire test, indicating the breaking-off of the hard coating materials was a smooth process, which in turn suggests a tenacious coating was obtained by the coating process.

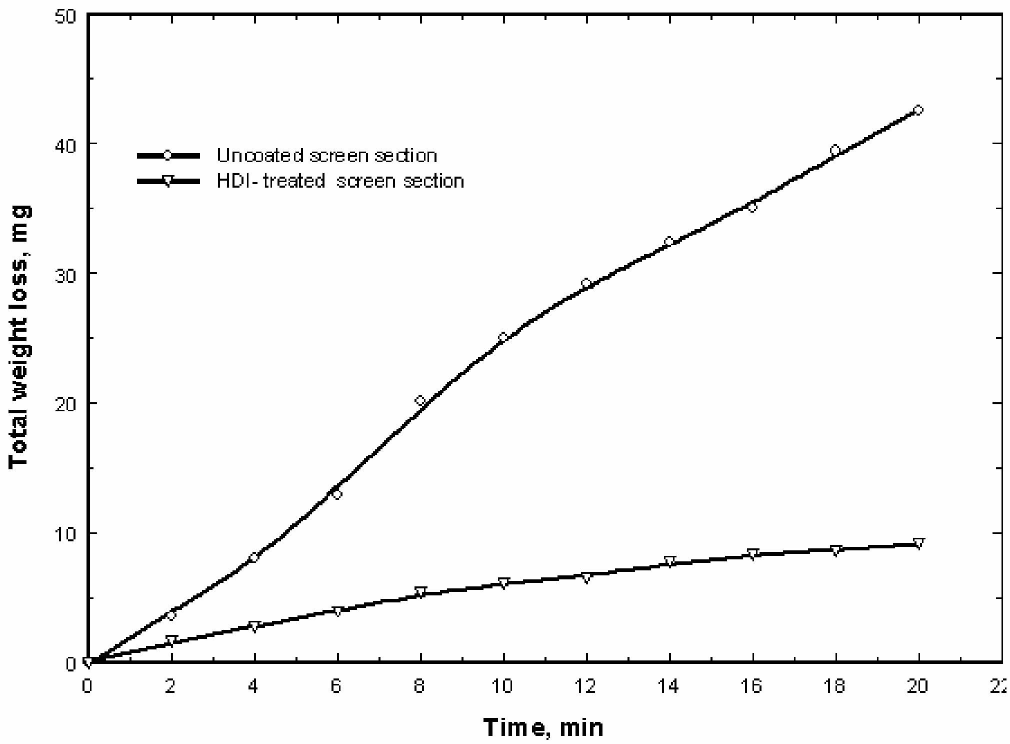


Figure 17. Block-on-ring wear test results

In most cases the wear test does not assess the properties of the coating alone; rather it evaluates the properties of the coating/substrate system which are important in dictating tribological performance. Therefore, the selection of wear test requires a careful assessment of uncoated components prior to any coating test program (Bull, 1997). It should be mentioned that in the actual coal preparation process wear is much slower but much more complicated than the wear created in the lab test. For example, vibrating screens are widely used for raw coal screening in coal preparation plants. Coal particles are fed onto the screen panels at a speed of 10-20 cm/s. In the meantime, the screen deck itself vibrates vertically to improve the probability for undersize coal particles to pass through the screen and report to the undersize product stream. Coal particles bounce up and down on the panel surface as they travel to the discharge end, which leads to impact wear when particles hit the screen panel. However, the vibrating amplitude of a raw coal screen is usually within 3-5 millimeters, thus sliding wear still dominates during screening process. Similar conclusion can be drawn on the wear of sieve bends and dewatering centrifuge. Thus, the wear test method employed in this study is suitable to simulate the wear conditions.

**New Wear Test Equipment**

Figure 18. Abrasive wear tester

The new laboratory abrasive wear test rig, as shown in Figure 18, includes three parts which are sand feeder, control panel and test unit. The sand feeder is magnetic vibratory feeder which can provide steady sand flow. The feeder speed controller, power switch and DC motor speed controller were bolted on the control panel. Test unit includes a funnel, a specially designed sand nozzle, a DC motor, a steel wheel, a lever arm, a specimen holder, weights, etc.

The sand used in this instrument is a rounded quartz grain sand as typified by AFS 50/70 Test Sand. According to ASTM G65, sand flow rate is required to be maintained at 0.66-0.88 lb/min. Therefore, the sand flow rate was calibrated by changing the frequency of the vibratory feeder. Figure 19 presents the calibration results in which the average flow rate was 0.69 lb/min with a standard deviation of 2.77%, suggesting that the sand flow rate can be well controlled by this machine.

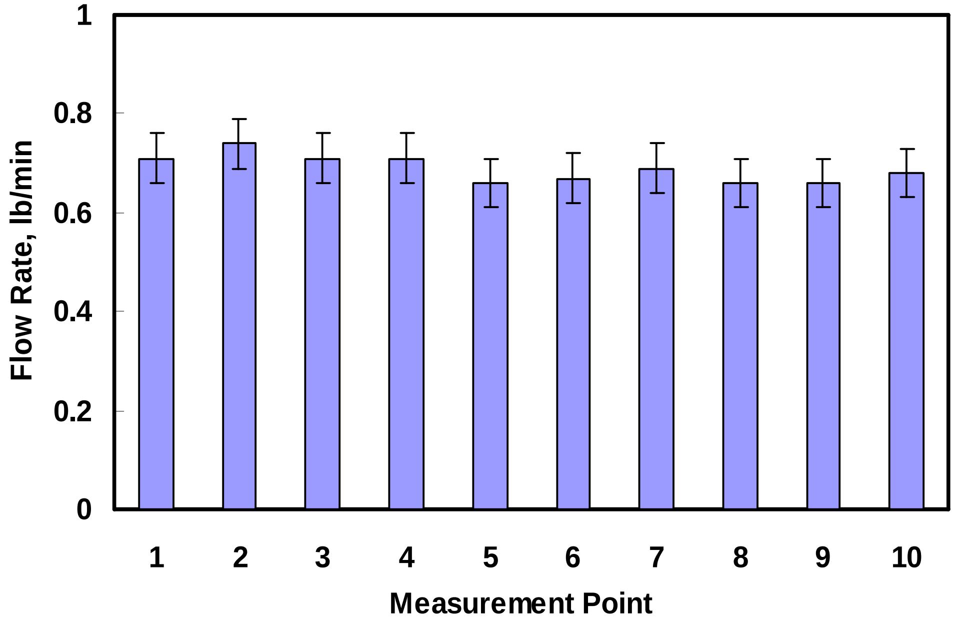


Figure 19. Calibration of sand flow rate

During a test steady sand flow is introduced between the test specimen and the rotating wheel of the test unit, as shown in Figure 20. A test specimen (e.g., a coated sample) is pressed against the wheel at a specified force by means of the lever arm, which creates abrasive wear on the specimen surface. The wheel used in this setup was made of C1018 steel and was heat treated to get a hard surface (HRC>60). The wheel was set on the shaft of the DC motor and rotates clock wisely thus its contact face moves in the direction of the sand flow. A mechanical counter was installed on the arm to count the revolutions of the wheel during a test. The pivot axis of the lever arm lies within a plane which is tangent to the wheel surface and normal to the horizontal diameter along which the load is applied.

Figure 20. Test unit

Upon the completion of calibrating the newly built lab wear tester, five uncoated specimens were tested to examine the performance of the tester. The sample was an AISI 4140 steel coupon with dimension of 3”×1”×0.25”. The applied load was 30 lbs and wheel speed was maintained at 200 rpm. Five test runs were performed and the weight loss of each specimen was presented in Figure 21. The standard deviation of the five test runs was 0.8% indicating that the consistent performance of the new wear test rig.

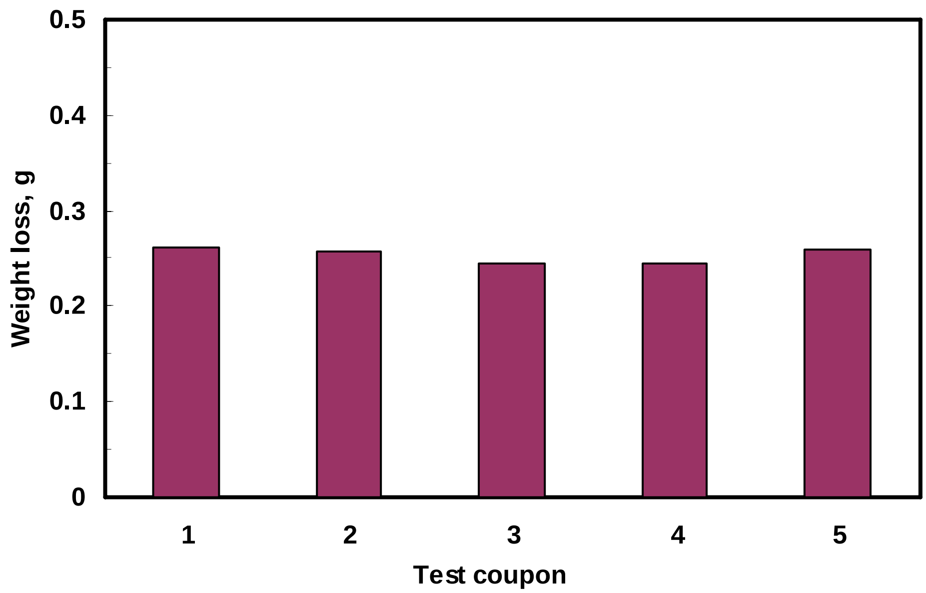


Figure 21. Abrasive wear test results of AISI 4140 steel

**On-site Testing**

Table 3 shows the field testing results of the three coated screen panels. It is known that the service life of an uncoated screen panel at the high wear position of the raw coal screen is about 5 weeks at the Plant, depending on the amount of coal processed. It can be seen that all the three panels outperformed the uncoated one in terms of service life. The high tonnages, range from 0.75 to 0.99 million tons, processed by the screen during test demonstrate the robustness of the three coated panels. If compared by wear rate which is defined as the ratio of test panel weight loss divided by the processing tonnage, No.9 showed the lowest wear rate among the three panels.

Table 3. On-site testing of three coated panels

| Test Panel | Date Installed | Date Replaced | Weight Loss, lb | Processing tonnage, ton/screen | Wear Rate, (lb/ton)×$10^{-7}$ |
|---|---|---|---|---|---|
| No.7 | 7/27/2005 | 10/7/2005 | 9.26 | 993955 | 93.16 |
| No.8 | 10/7/2005 | 11/28/2008 | 7.87 | 867321 | 90.74 |
| No.9 | 2/16/2006 | 4/5/2006 | 6.61 | 747384 | 88.44 |

Figure 22 compares a test panel before and after test. It can be seen that the screen slots have deformed from the initial square to trapezoid-shaped after the test. The mainly reason is coal particles hit the bar between two adjacent slots and the thus the wires become thinner due to wear caused by the moving coal particles. Therefore, the wire between two slots is the most vulnerable part of a screen panel.

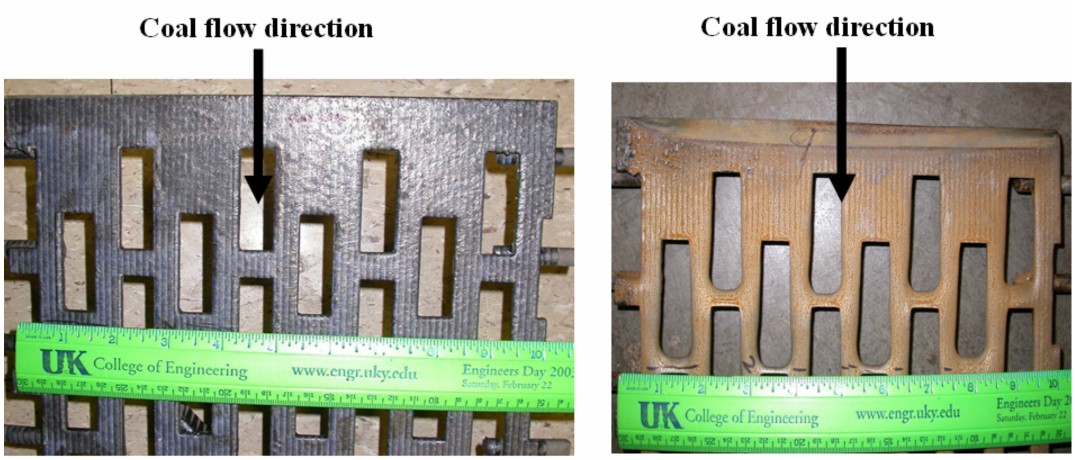


Figure 22. Test panel (Left:before test; Right: after test)

As mentioned earlier that the opening size change of specified apertures were measured for each test panel, which can be translated into slot area change. Here a "slot area increase rate" is proposed which is defined as the area ratio of a slot after and before test. For the purpose of comparison, the area change ratios of four rows, Row 2, 10, 20 and 30, are shown in Figure 23 to 26 .

It can be seen that for all the three test panels, the area increase of the slots in the upper portion (close to feeding end) is higher than that of the lower portion (close to discharge end). This is due to the fact that slots close to the feeding end are subject to process more materials than that on the discharge end, which, in turn, creates more wear on the upper portion of the screen panel. Another finding, on each panel, the size change (area increase) of the slots on the second column is higher than that of the other three measured slots. This is because the test panel was installed right next to the wall and coal particles hit the wall and bounced back to the panel on approximately the second column.

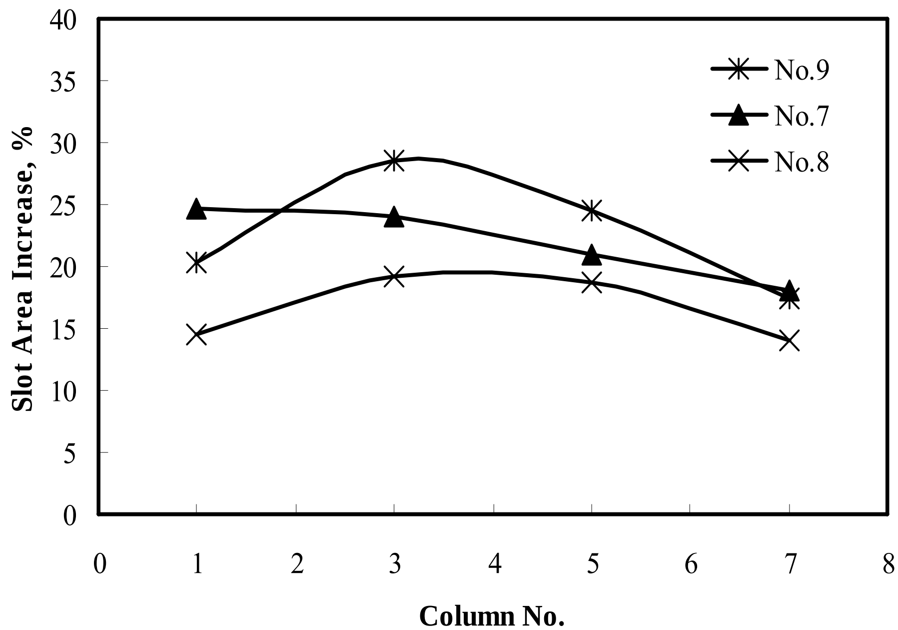


Figure 23. Slot area change of Row 2

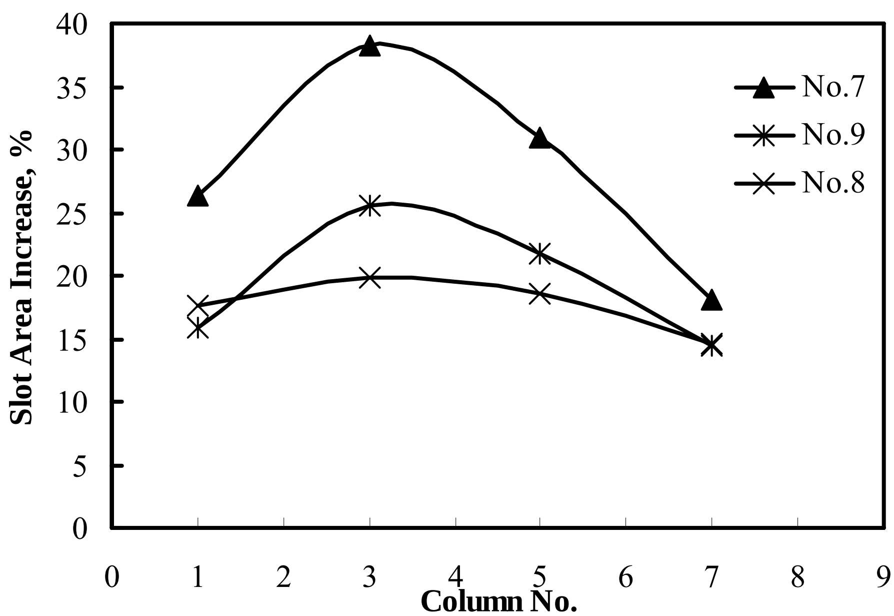


Figure 24. Slot area change of Row 10

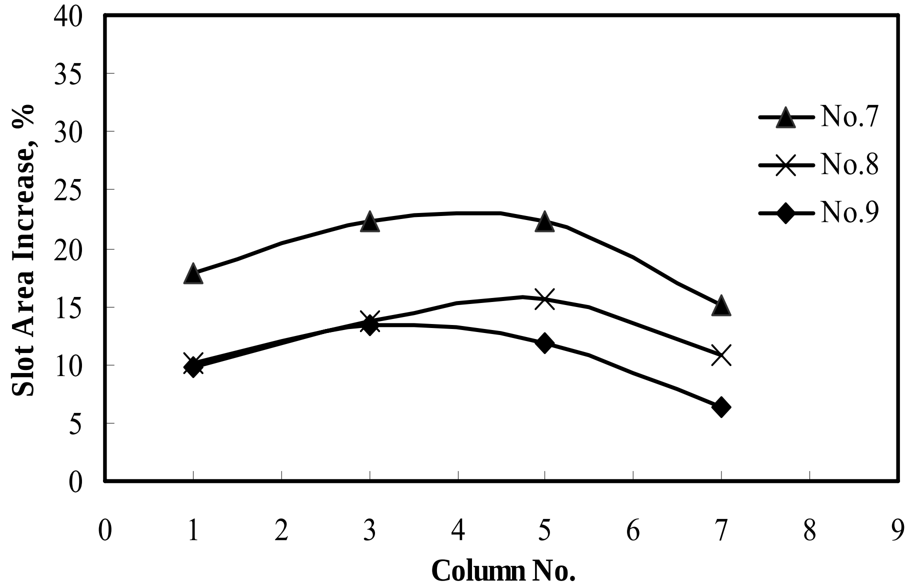


Figure 25. Slot area change of Row 20

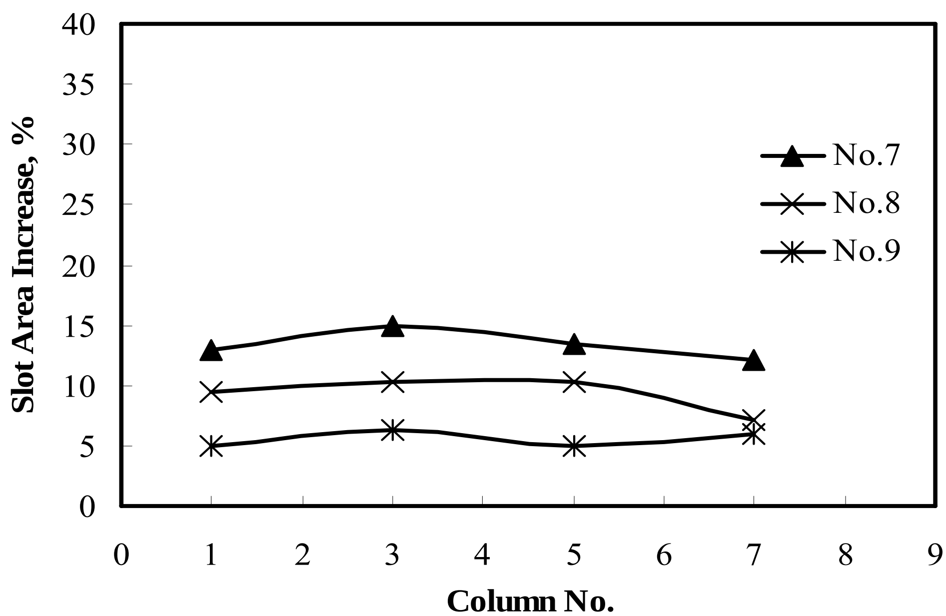


Figure 26. Slot area change of Row 30

As shown in Figure 22, the wires between two adjacent slots are the most vulnerable part on the screen. Actually, although the screen panel was replaced after putting in service for some time, the laser tracks can still be seen on the panel (Figure 22) and the slots close to the discharge end almost stayed intact, e.g., the slot area change of the Row 30 of Screen No.9 is only about 5% (Figure 26), suggesting the high toughness of the surface coating. If the wear resistance of the slots near the feeding end can further improved, the service life of a coated panel will be greatly improved. Coating the wires and inner wall of the slots has been thought to be a solution to this issue. Thus, in the next year, part of the research efforts will be focused on improvement the flexibility of the coating method to make it enable to coat the most vulnerable part of a screen panel.

It should be noted that the in-service wear conditions are much more complicated than that of the laboratory wear test. In realities, a component usually fails by a mixture of wear modes, which makes it difficult to simulate in the lab testing. Coated components will be subjected to different wear tests to examine the coating performance in the coming research period.

# CONCLUSIONS

Based on the results obtained in the present investigation, the following conclusions can be drawn:

1. HDI surface coating process was introduced for enhancing the surface wear resistance of raw coal screen panels used for coal preparation.

2. A uniform and crack-free Thermite+WC coating which was metallurgically bonded to the substrate was achieved. Refined coating microstructure was obtained in the coating. WC phases and dendrites uniformly distributed in coating which is beneficial to improve the coating wear resistance.

3. The coated component showed increased microhardness as well as enhanced wear resistance compared to the untreated sample, which demonstrated a considerable potential of applying HDI coating process to extend mineral processing devices.

4. A new wear test rig was successfully built and initial tests have demonstrated highly consistent results using this machine. Both block-on-ring and abrasive wear will be tested for the newly developed coatings in the coming research year, which will provide further insight into understanding the wear performance of the coated components.

5. On-site test using coated screen panels exhibited sound improvement of screen panel service life. In the mean time, the major problems with the coated panels have been identified. Coating system/facilities are under improvement to address these issues and to further extend the life span of the coated components.

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